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Abstract

The rotation of the solar corona has been studied using recurrence properties of the green coronal line (5303Å) for the interval 1947-1970. Short-lived coronal activity is found to show the same differential rotation as short-lived photospheric magnetic field features. Long-lived recurrences show rigid rotation in the latitude interval ± 57°.5. It is proposed that at least part of the variability of rotational properties of the solar atmosphere may be understood as a consequence of coexistence of differential and rigid solar rotation.

RIGID AND DIFFERENTIAL ROTATION OF THE SOLAR CORONA

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This study of coronal rotation uses synoptic tables of the intensity of the green coronal line (5303Å) for the years 1947-1970. These tables were prepared by Sýkora (1973, personal communication) on the basis of intensity measurements published in Quarterly Bulletin on Solar Activity. The intensity is expressed in the Pic du Midi photometric scale. The coronal intensity for the central meridian was calculated as an average of intensities measured at the limbs 7 days before and 7 days later respectively. In the table Sýkora gives the intensity as 3-day averages every third day for six latitudinal zones 20° wide. The zones are centered at $47\overset{\circ}{.}5$N, $27\overset{\circ}{.}5$N, $7\overset{\circ}{.}5$N, $7\overset{\circ}{.}5$S, $27\overset{\circ}{.}5$S, and $47\overset{\circ}{.}5$S respectively. We have interpolated one day values from the tables.

It is clear that the resulting data sets have been extensively smoothed so that only long-lived and large-scale coronal features are left. However, for an investigation of coronal rotation this property of the data seems to be an advantage. On the other hand very long period variations (such as the 11 year sunspot cycle) are not desirable and have been removed by subtracting a running 27-day average from the data. The six time series (one for each latitude zone) were then autocorrelated with a lag varying from 0 to 60 days or more, to investigate the recurrence tendency and recurrence

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period which we interpret as the <u>synodic rotation period</u> for the coronal features. This implies that we assume that any systematic coronal movements in longitude during one rotation are negligible.

Figure 1 shows the autocorrelations out to a lag of 60 days for two 3-year intervals centered on 1951 and 1968, corresponding to years in the declining portion and to years in the rising portion of the sunspot cycle. The recurrence tendency is equally marked; the autocorrelation coefficient is of the order +0.5 for the peaks near 27 days. This indicates that stable coronal features do exist and may be traced using the green line intensity. We intend to use these features as tracers to determine the solar rotation period for each of the six latitude zones. Generally the peaks are well formed so that a determination of the recurrence period with an accuracy of about 0.1 day is possible.

An interesting feature in Figure 1 is that the rotation period is nearly constant 27.0 days for all latitudes during the years 1950-1952, showing no sign of the usual differential rotation, which is evident during the 1967-1969 interval. To investigate if the lack of differential rotation is reproducible and characteristic for certain parts of the sunspot cycle, autocorrelations like the ones in Figure 1 were computed for 3-year intervals sliding through the data one year at a time. The rotation period for each interval was determined as the recurrence period of the peak near 27 days. The result is shown in Figure 2, as function of phase within the sunspot cycle. The two hemispheres have been combined as well as have the two sunspot cycles (1947-1957, 1958-1969). The individual hemispheres, and sunspot cycles, show very much the same general behavior as the average depicted in Figure 2.

For the low latitude zones (centered at $7\overset{\circ}{.}5$) the rotation period is nearly constant 27.0 days throughout the cycle. The high latitude zones ($47\overset{\circ}{.}5 \pm 10^{\circ}$) show an increase in rotation period as new solar activity begins at high latitudes about 2 years before sunspot minimum and reach a rotation period of 29.4 days 1-2 years before sunspot maximum. Then the period decreases during the declining phase of the cycle to reach a low of 27.8 days on the average. In individual years the period may go as low as 27.0 days, as we saw in Figure 1. In the middle latitudes ($27\overset{\circ}{.}5 \pm 10^{\circ}$) an increase in rotation period to a high of 27.8 days begins 2 years before sunspot maximum. After the maximum the rotation period again decreases to 27.2 days.

We interpret these changes as a result of the equator-ward migration of solar activity throughout the cycle (Spörer's law). If we assume that active regions and associated coronal features participate in the differential rotation of the photosphere, then we should expect the corona at a given latitude to show differential rotation at least when activity is high at that latitude. This is evidently the case at high latitudes at the start of a sunspot cycle, and at medium latitudes at sunspot maximum. So when activity moves from high to lower latitudes the portion of the corona overlying the activity tends to corotate with the activity probably due to influence of the magnetic field of the active regions. Strictly speaking we should say that the intensity maxima corotate with the activity.

There is no difficulty in understanding why the corona follows the differential rotation of the activity when it is there. The question which Figure 2 raises is: why does the corona show little or no differential rotation when the activity has decayed away? Judging from Figure 2 we get the impression that the degree of differential rotation decreases when activity in the particular latitude zone decreases. Is it possible to extrapolate to zero activity and determine the resulting rotation period?

The amplitude of the second peaks (near 54 days) in Figure 1 is not very much less than that of the first peak. Indeed we find by increasing the lag of the autocorrelation that prominent peaks may exist for lags corresponding to several years during certain intervals. An example is given in Figure 3 for the high latitude zone (+47°.5) in the northern hemisphere during the four years 1949-1952. The n^{th} recurrent maximum is at a lag of τ_n days. A synodic rotation period P_n can then be associated with the n^{th} peak as $P_n = \tau_n/n$. Features in the corona with a lifetime of a few solar rotations will dominate the rotation periods associated with the first few values of the recurrence number n, but will have little effect on the rotation periods corresponding to large values of n, since only features whose lifetime equals or exceeds τ_n can contribute to recurrence peak number n.

Figure 4 shows values of P_n for n up to 11 from autocorrelating all 24 years of data. Periods for the two hemispheres are again combined in this figure. For n larger than 11 some of the peaks become difficult to distinguish so we limit the investigation to these 11 first well defined peaks. Most solar activity have lifetimes much less than 11 x 27 $\approx$ 300 days, and one can make the statement that there are fewer and fewer surviving active regions as n increases from 1 to 11. For the first peak (n = 1) differential rotation is obvious. The rotation periods P_1 for the three latitude ranges are close to the average periods over a sunspot cycle as seen in Figure 2. As n increases more and more, activity dies away and the rotation periods P_n for the three latitude zones converge to a value slightly larger than 27 days. The implication is that short-lived coronal features show differential rotation, while features with lifetimes of the order of about 1 year or more do not show differential rotation but instead all rotate in ≈ 27 days independent of latitude.

Similar effects have been found in an analysis of the photospheric magnetic field [Wilcox et al., 1970], in analysis of the interplanetary magnetic field observed by spacecraft [Wilcox and Tanenbaum, 1971], and in analysis of the interplanetary magnetic field inferred from polar cap geomagnetic variations from 1926 to 1971 [Svalgaard, 1972]. All these analyses show that short-lived features rotate slower than long-lived features and may be interpreted in the same way, namely that features associated with active regions show differential rotation while long-lived features show rigid rotation with period ≈ 27 days independent of latitude.

Figure 5 is a composite of the relationship between recurrence period P_n and peak number n for the high latitude ($47\overset{\circ}{.}5$) green line corona for the photospheric magnetic field at 25°N latitude and for the inferred interplanetary magnetic field. Differential rotation is evident for peak numbers less than about 10, while rigid rotation seems to be present at all latitudes for n larger than 10. Classically, sunspots and active regions participate in differential rotation. The solar magnetic sector structure (Wilcox and Howard, 1968), discovered by comparing spacecraft observations of the interplanetary magnetic field with observations of the photospheric magnetic field, appears to rotate rigidly with a synodic period near 27 days. Our results support the viewpoint that rigid rotation exists, and our conjecture is that structures in the solar atmosphere may be divided into two classes: small scale (both spatially and temporally) regions of activity having differential rotation, and large scale background structures rotating rigidly at all latitudes. One such rigidly rotating feature has been discussed by Wilcox (1973). During the years 1968-1969 a persistent large scale coronal magnetic structure associated with a sector boundary was observed as a magnetic arcade loop structure extending from one polar region to the other in approximately the North-South direction. This structure was seen on computed coronal magnetic field maps for days on which a solar magnetic sector boundary was near central meridian.

That the coronal structures which show differential rotation are related to magnetic fields in the underlying photosphere may be inferred from Figure 6, where the maximum rotation periods found for each latitude zone in the coronal green line data are compared with the rotation periods of the photospheric magnetic field deduced by Wilcox and Howard, (1970). In both cases the periods P_1 of the first recurrence peak are plotted to bring out properties of the differentially rotating component of the solar structures. We find that the active corona has the same differential rotation as the short-lived photospheric magnetic field features. In the lower part of the figure is shown the rotation periods of the long lived ($n = 11$) coronal features, displaying the characteristics of rigid rotation.

The variety of rotational properties of the photospheric, coronal and solar wind (interplanetary) plasma and magnetic fields presents an intriguing problem in solar physics. We propose that at least part of that variation may be understood as a consequence of the coexistence of differential and rigid solar rotation. Since the period of the rigid rotation is close to the equatorial rotation rate (27 days) we raise the question if differential rotation is due to an equatorial acceleration or to a polar spin down? The latter possibility seems more favorable if the concept of rigid rotation at near the equatorial period is accepted. Evidence for the rigid rotation can, as we have seen, be found at several heights of the solar atmosphere ranging from the photosphere to the orbit of the Earth.

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FIGURE CAPTIONS

Fig. #

1 Autocorrelation functions for lags varying from 0 to 60 days of the intensity of the coronal green line (5303 Å) for two intervals 1950-52 and 1967-69. The vertical distance between the lines labeled 0.0 corresponds to an ordinate difference of 1.0. Six latitudinal zones have been examined; the zone limits are given on the figure. Vertical lines are drawn corresponding to recurrence periods of 27 and 54 days respectively.

2 Recurrence period for the primary recurrence peak for autocorrelations of 3-year intervals sliding through 1948-1969 one year at a time. The results from the northern and the southern hemisphere have been averaged and plotted corresponding to the phase within the sunspot cycle for the central year of the interval. The figure therefore shows the average sunspot cycle variation of the recurrence period. The three latitude zones are high latitude (HL) centered at $47\overset{\circ}{.}5$, medium latitudes (ML) centered at $27\overset{\circ}{.}5$, and low latitude (LL) centered at $7\overset{\circ}{.}5$. In the lower panel is shown the migration of sunspots in latitude trough the sunspot cycle. The boxes indicate schematically the regions in latitude-time space where differential rotation is prominent in the corona.

3 Autocorrelation function for the high northern latitude zone ($47\overset{\circ}{.}5$) for the interval 1949-1952. The autocorrelation was lagged out to 500 days. The definition of the lag time τ_n for the n^{th} peak is shown.

4 Variation of coronal recurrence period P_n with the peak number n for all data 1947-1970. The two hemispheres are combined. Solid dots show the variation for the high latitude zone, crosses for medium latitudes, and circles with a cross for the low latitude zones.

5 Relationship between recurrence period and peak number for high latitude green line coronal intensity maxima (lat. $47\overset{\circ}{.}5$, shown by open circles), photospheric magnetic field (25° N, filled circles), and inferred interplanetary magnetic field (circles with crosses).

6 Some of the varieties of solar rotation. The solid curve represents the classical results of Newton and Nunn (1951) for long-lived sunspots. The circles are average results for large-scale photospheric magnetic fields (Wilcox and Howard, 1970). The crosses are results obtained by Howard and Harvey (1970) from Doppler shifts of Frauenhofer absorption lines. The rotation periods of the green line corona during active intervals are shown as filled squares and agree closely with the photospheric magnetic field rotation periods.

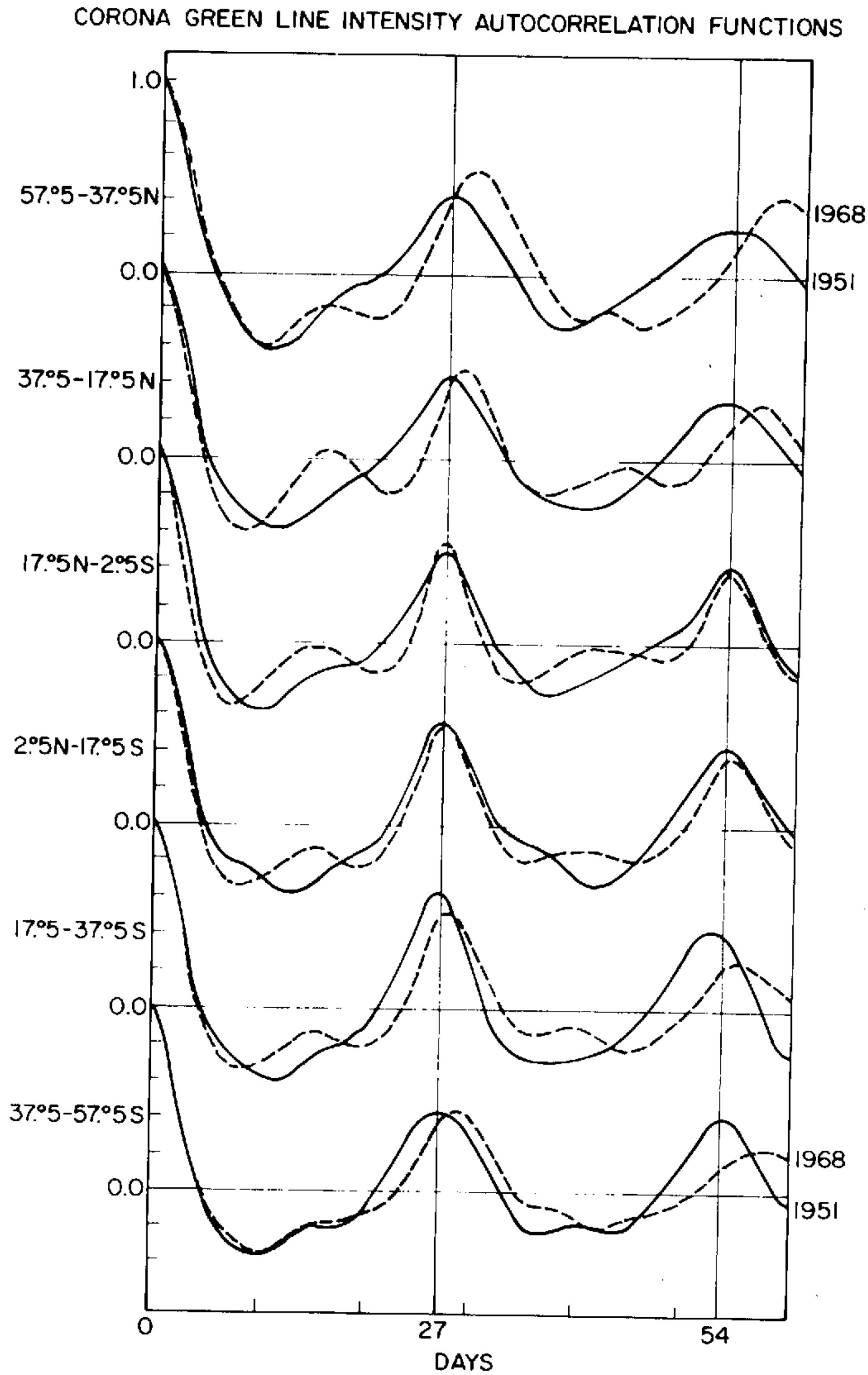

CORONA GREEN LINE INTENSITY AUTOCORRELATION FUNCTIONS
1.0
57.°5-37.°5N
0.0
37.°5-17.°5N
0.0
17.°5N-2.°5S
0.0
2.°5N-17.°5S
0.0
17.°5-37.°5S
0.0
37.°5-57.°5S
0.0
1968
1951
1968
1951
0
27
54
DAYS

Figure 1.

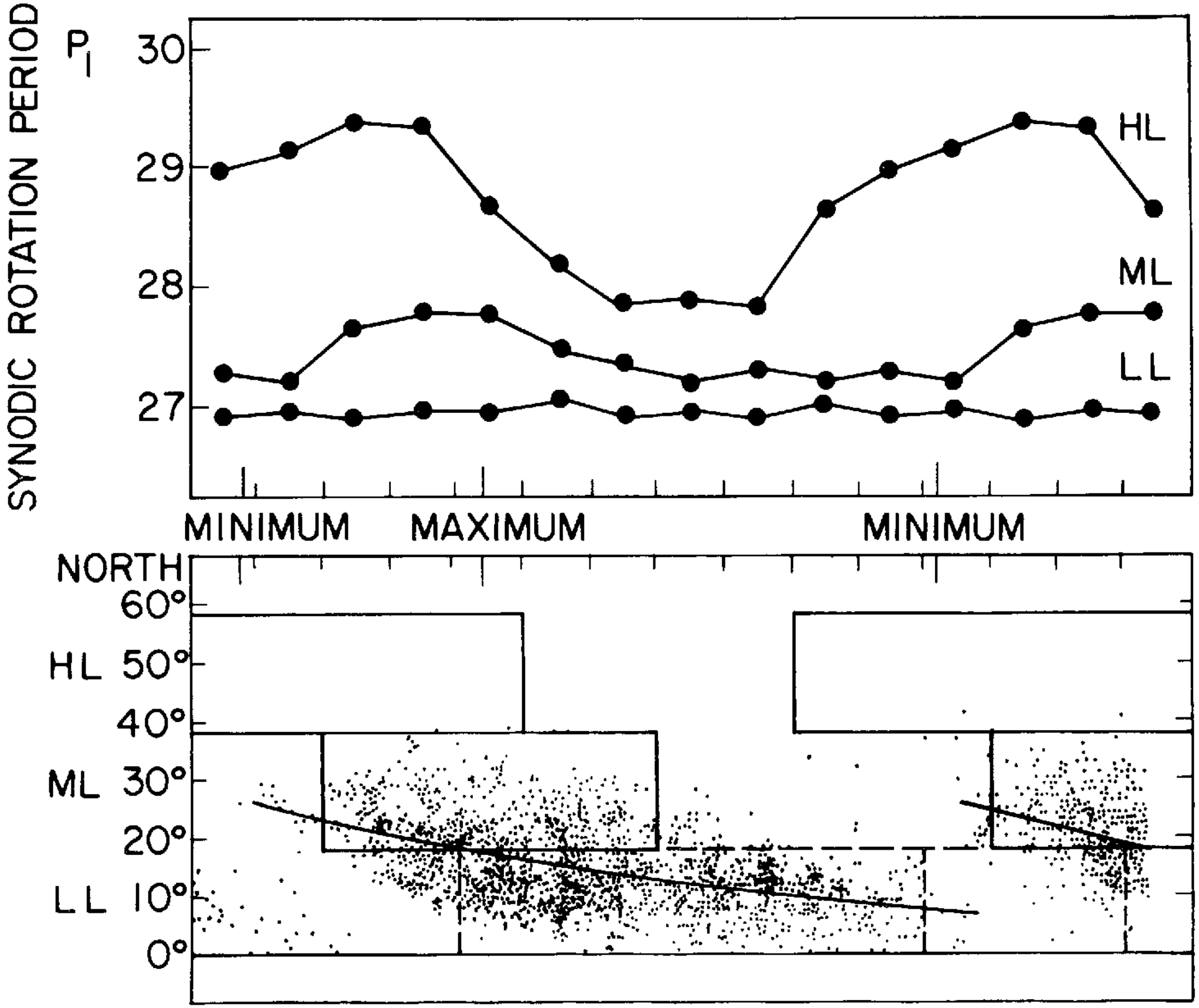

SYNODIC ROTATION PERIOD
P_1
30
29
28
27
HL
ML
LL
MINIMUM
MAXIMUM
MINIMUM
NORTH
60°
HL 50°
40°
ML 30°
20°
LL 10°
0°

Figure 2.

CORONA GREEN LINE INTENSITY AUTOCORRELATION FUNCTION
1949-1952

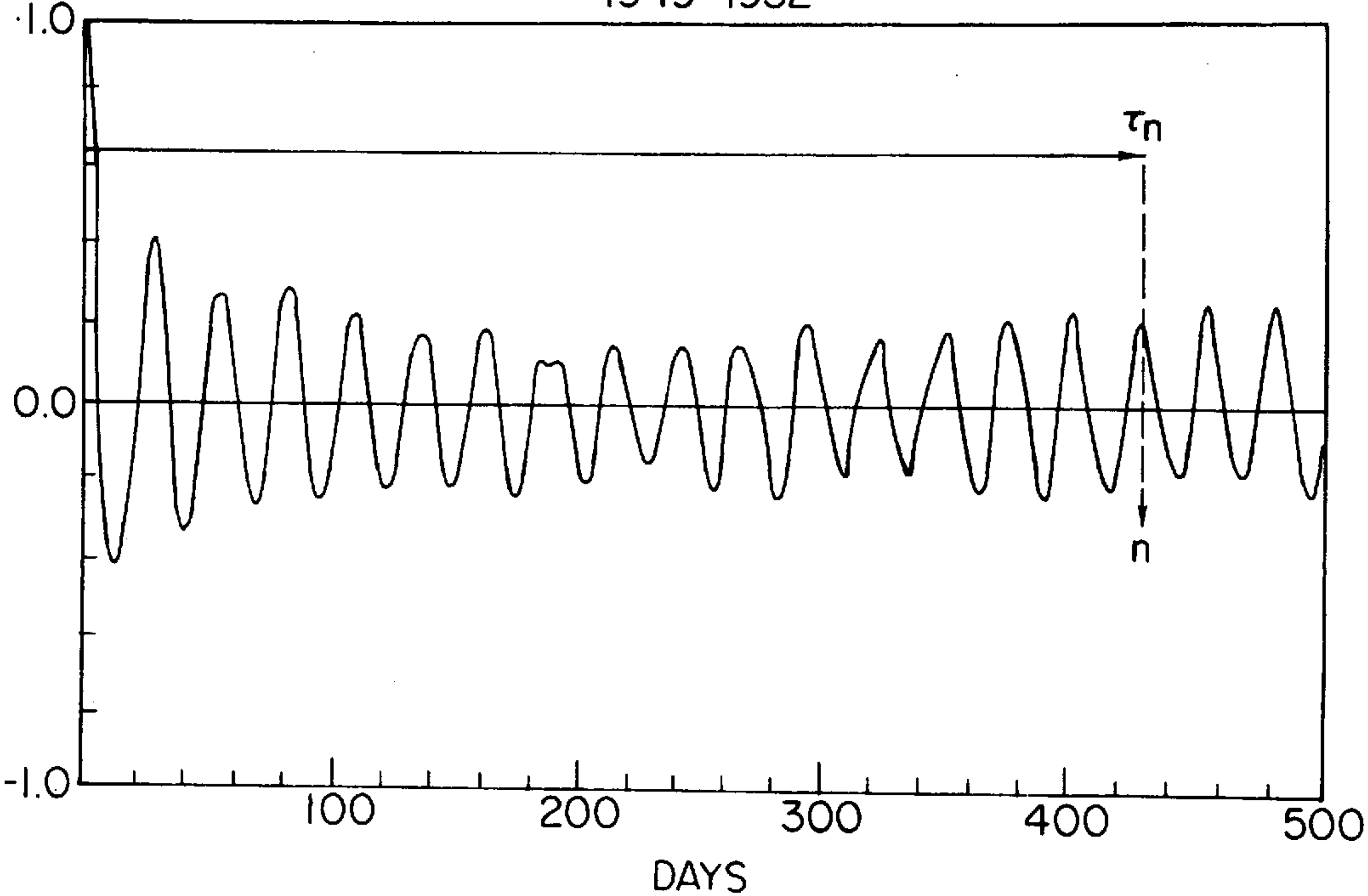
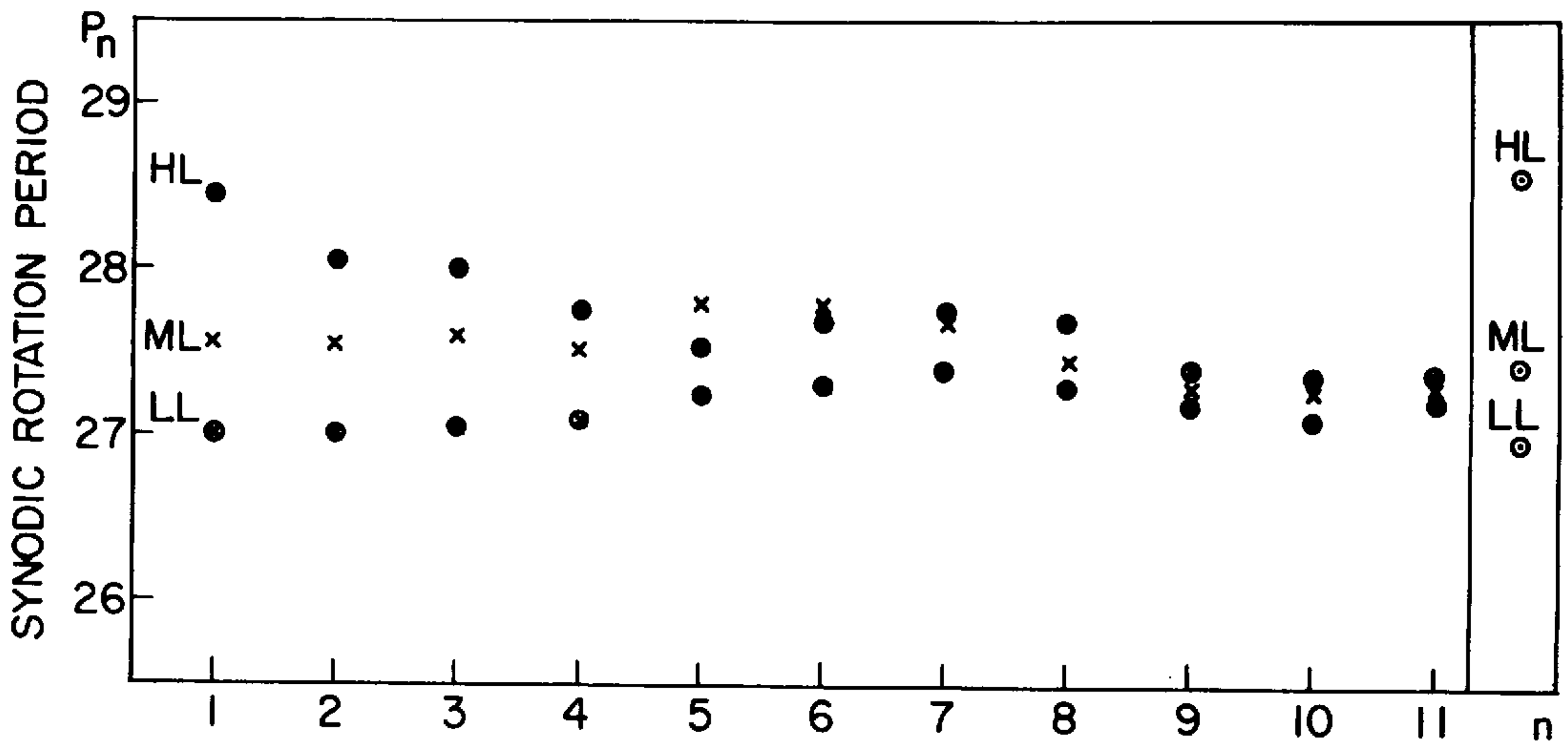


Figure 3.



P_n
SYNODIC ROTATION PERIOD
29
28
27
26
HL
ML
LL
1
2
3
4
5
6
7
8
9
10
11
n
HL
ML
LL

Figure 4.

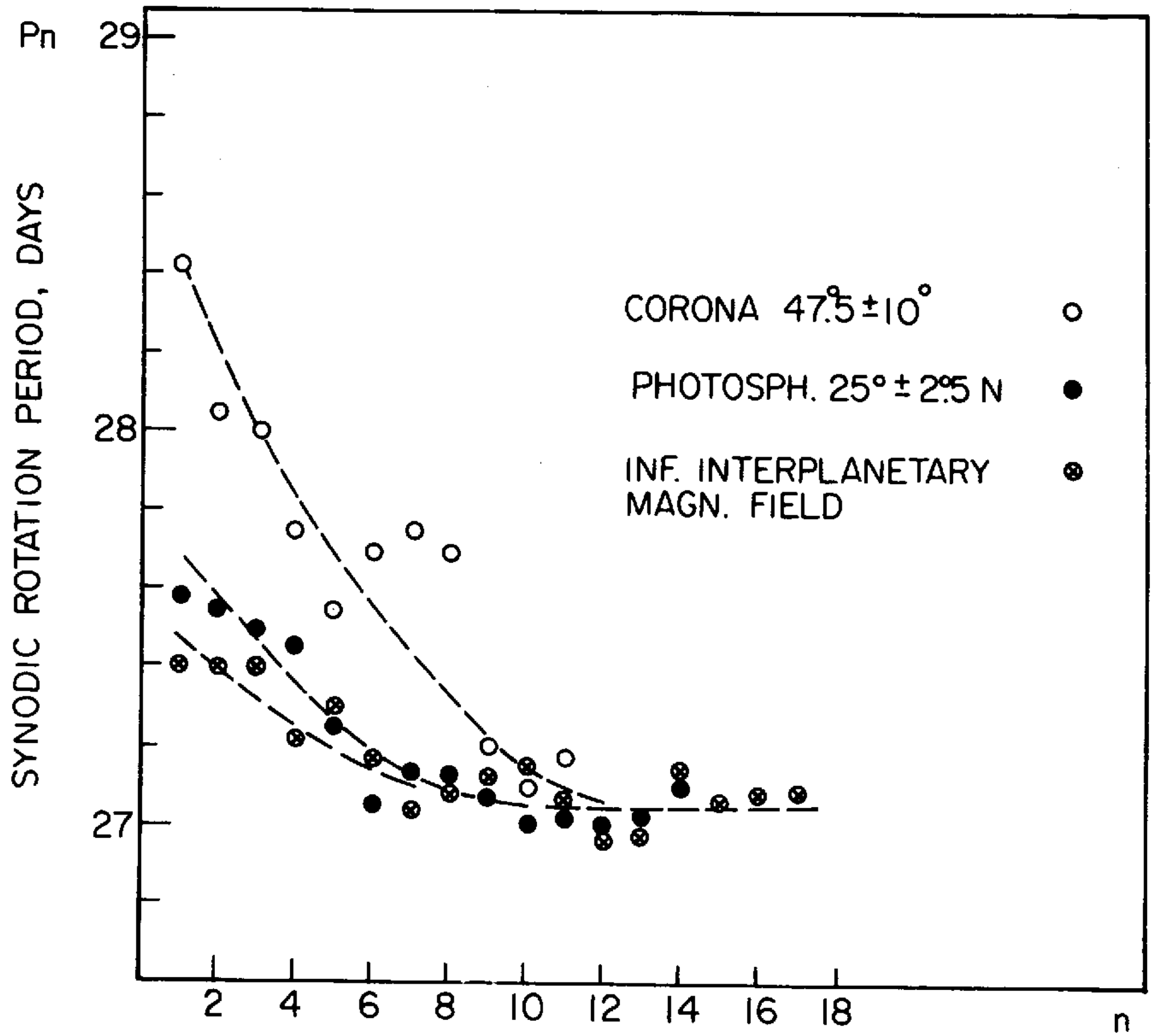

Pn
29
28
27
SYNODIC ROTATION PERIOD, DAYS
CORONA 47.5° ± 10°
PHOTOSPH. 25° ± 2.5° N
INF. INTERPLANETARY
MAGN. FIELD
2
4
6
8
10
12
14
16
18
n

Figure 5.

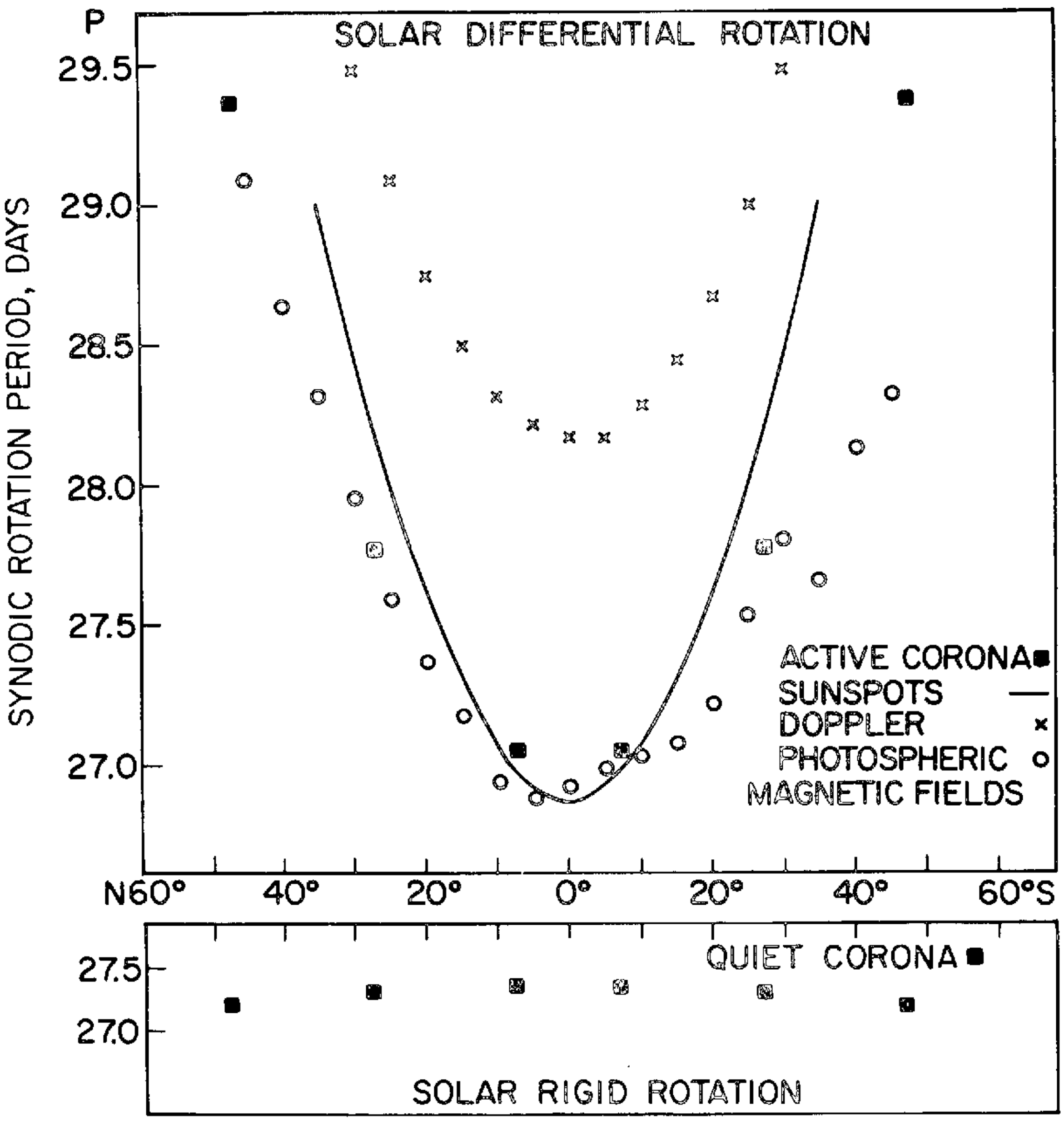

P
SOLAR DIFFERENTIAL ROTATION
29.5
29.0
28.5
28.0
27.5
27.0
SYNODIC ROTATION PERIOD, DAYS
ACTIVE CORONA
SUNSPOTS
DOPPLER
PHOTOSPHERIC
MAGNETIC FIELDS
N60°
40°
20°
0°
20°
40°
60°S
QUIET CORONA
27.5
27.0
SOLAR RIGID ROTATION

Figure 6.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
SOLAR ROTATION						
SOLAR CORONA						

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13. ABSTRACT

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